Importance of Proton-Nucleus Strong Interaction to Proton-Radiography Simulation

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The use of high-energy protons (20–50 GeV) to probe the internal structure of thick objects has added a new dimension to radiographic studies. One may mention [1], among other studies:

1. The mean free path λ of high-energy protons is much longer than that of x-rays. The huge difference in the mean free paths has an important consequence. For example, the beam attenuation factor (N_0/N) of high-energy protons in C, Fe, Pb with a thickness 200 g/cm^2 are 28, 11, and 6, respectively, while those of 15-MeV x-rays are 30, 518, and 66910. In other words, high-energy protons penetrate much deeper into materials.
2. The proton is a charged particle. It, therefore, interacts with material through both the electromagnetic and strong nuclear interactions, thus providing valuable information on the material compositions, such as the ratio Z/A, of the targets.

There is a coordinated effort at Physics (P), Applied Physics (X), Los Alamos Neutron Science Center (LANSCE) and Theoretical divisions in understanding the proton-radiography technologies. While the multiple p-nucleus electromagnetic interaction can be calculated with the aid of multiple Coulomb scattering theories [2], any Monte Carlo type simulation of multiple nuclear scattering in a thick object needs proton-nucleus differential cross sections as the basic input. However, in the literature there are only sparse data available at proton-radiography energies.

We have developed an eikonal optical model for proton-nucleus scattering and provided differential cross sections for 18 nuclei/isotopes ranging from A = 3 (triton) to A = 239 (plutonium) at a fine incoming proton momentum interval between 1 and 50 GeV/c. Our model predictions agree well with the data available in the open literature. They also agree with the results given by the Glauber model for nuclei having A ≤ 12.

Our cross sections have been used by the Diagnostic Methods Group (X-5) in their MCNP code and have since been used by LANSCE in their simulations. One example of the important effect of p-nucleus elastic scattering is shown in Fig. 1 [3]. In this

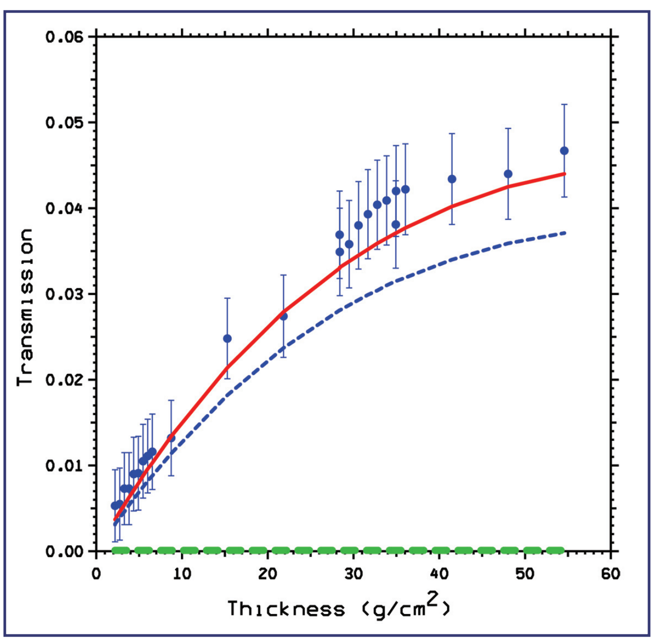

Figure 1—
Comparison of a PRAD simulation by Neri and Walstrom [3] with Carbon step-wedge data measured at incident proton momentum 23 GeV/c. The data are given in blue with error bars attached. The simulations given by using MCS alone, using MCS together with elastic nuclear scattering, and using MCS, elastic nuclear scattering, quasielastic nuclear scattering are represented, respectively, by the green, blue, and red curves.

figure, the data are from Experiment EA955 performed at Brookhaven National Laboratory with a proton beam of incident momentum 23 GeV/c. The figure gives the dependence of the transmission coefficient as a function of target thickness. In this particular measurement in order to enhance the contrast of proton radiographic image, an anti-collimator was used to block the outgoing protons at angles between 0 and 4.56 mrad. As we can see, if only the multiple Coulomb scattering (MCS) is considered in the simulation, the predicted transmissions will be nearly zero (the green line), which clearly disagree with the data. However, when the p-^{12}C elastic differential cross sections provided by T-16 are taken into account, the blue curve is obtained. This curve illustrates the dramatic effect of nuclear scattering. A further improvement has been noted when p-nucleus quasielastic (QEL) scattering is also taken into account (the red curve).

To understand the result in Fig. 1, I present in Fig. 2 the p-^{12}C Coulomb and nuclear elastic scattering, separately. As we can see, the Coulomb scattering is dominant only within a very small solid angle which is almost completely blocked by the collimator. What were observed are, in fact, almost entirely due to nuclear scattering beyond the collimator cutoff angles.

The QEL scattering cross sections used for generating the red curve in Fig. 1 were modeled in Ref. [3], where one assumed

$$(d\sigma/d\Omega)^{q.el.}_{pA} = A_{eff} \times (d\sigma/d\Omega)^{el}_{pp}$$

with A_{eff} being a parameter. Here, the subscripts *pA* and *pp* refer, respectively, to proton-nucleus and proton-proton. This class of model has also been extensively used by other research groups. However, it can underestimate the QEL contribution because the model uses essentially the 2-body *pp* kinematics. As high-energy protons easily fragment the nucleus, we are currently developing a QEL model which takes into consideration the many-body aspect of the kinematics and dynamics. Preliminary results indicate that our model gives bigger QEL contributions.

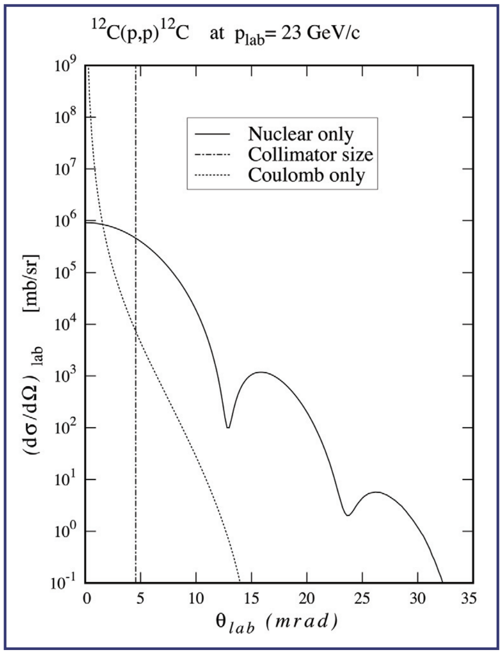

***Figure 2—* Calculated proton-12C Coulomb and elastic differential cross sections for incident proton momentum 23 GeV/c. The anticollimator blocks the beam scattered into angles between 0 and 4.56 milliradians.**

In summary, it has been demonstrated that proton-nucleus elastic and quasielastic scatterings play a significant role in proton radiography. We are currently developing a refined model for quasielastic scattering. We will also model diffractive production, another important p-nucleus strong interaction channel that has not been fully studied. We are confident that a precise simulation of proton radiographic process will soon be available.

[1] Communication from Physics Division.
[2] G. Molière, *Z. Naturforsch*, **3a**, 78 (1948); an English version of the theory can be found in H.A. Bethe, *Phys. Rev.* **89**, 1256 (1953).
[3] F. Neri and P.L. Walstrom, "A Simple Empirical Forward Model for Combined Nuclear and Multiple Coulomb Scattering in Proton Radiography of Thick Objects," Los Alamos National Laboratory report LA-UR-03-9011 (December 2003).

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